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A new approach to evaluate the effectiveness of rockfall barriers

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Abstract

The paper addresses the response of a semi-rigid rockfall protection barrier using numerical models. The study show a large dependence of the barrier response to the impact conditions. The block size and impact position, rather than the velocity direction and magnitude induce different modes of failure of the fence, which in turn result in different values of failure energy. As a result, the barrier capacity cannot be established in a deterministic way. The effectiveness of structures as such can be more successfully evaluated through a reliability probabilistic approach. Results can be used to create a meta-model of the barrier response which can be incorporated into rockfall simulation models, enabling a reliable and comprehensive design of rockfall mitigation interventions performed with this type of structure.

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Keywords: Rockfall mitigation; FEM; probabilistic approach; rockfall simulation models

1. Introduction

The nominal capacity of flexible rockfall protection barriers is now established based on results of full scale tests on prototypes, following standardised procedures [1]. This type of barrier dissipates the energy possessed by an impacting block through the development of large plastic deformation of the interception structures and energy

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dissipating devices mounted on cables. Numerical studies, recently carried out on barrier models, adequately calibrated on the base of experimental results [2] have shown that the response of flexible barriers is not significantly affected by various impact conditions [3]. Although their use is widespread and their presence is very frequent along many potentially unstable areas, few information is found on the response of semi-rigid barriers. This type of protection barrier is generally installed in areas threatened by rockfall event of low to medium intensity to arrest blocks falling with low values of kinetic energy, without the support of standardized prescription and no full-scale tests are requested.

Only in the last few years, the response of these protection structures has been investigated, led by the need of predicting the ability of existing barriers to withstand the impact of blocks of given mass and velocity to perform residual rockfall risk assessments [4,5]. A numerical procedure, based on experimental data used for flexible barrier was considered in the attempt of assigning a threshold value of capacity to semi-rigid barriers of various dimensions and geometry. Results have shown that a maximum capacity of about 200 kJ could be achieved [6]. The need of improving the response of this structure type in New South Wales (Australia) has also led, in recent years, to the development of an advanced experimental set up for testing prototypes of semi-rigid barriers to impact energies of about 30 kJ [7]. These experiments, which included tests on barrier components, enabled to improve and calibrate existing models of semi-rigid barriers. The models were used to run preliminary parametric analyses addressing the size of the impacting block. Results showed that variation in block dimensions largely affects the energy required to rupture the fence [8,9].

Following these results, the paper analyses the impact response of a barrier of the semi-rigid type to the variation of a set of important parameters: block size, speed and position within a realistic range. Results are used to describe comprehensively the response of this barrier type. A probabilistic approach is then shortly proposed to interpret, in a reliable way the numerically observed behaviour, following a method recently proposed in [10].

2. The numerical response of a semi-rigid barrier

A semi-rigid barrier is generally made of longitudinal cables attached to steel structural posts fully restrained at the ground. A secondary light steel meshwork is typically found as secondary interception structure. The study addresses the response of a rockfall barrier of this type, whose presence is wide within the Alpine arc. Other models can be encountered, featuring a geometrical configuration very similar to this. Pictures of the barriers are shown in Fig. 1a, while a schematic representation of the FE model is shown in Fig. 1b. The model was first devised in [6] and then improved, calibrated and assessed using results of the experimental study presented in [11]. The barrier is made of steel post fixed at the base, longitudinal cables evenly spaced and a hexagonal meshwork. Side cables connect the outermost posts to the ground.

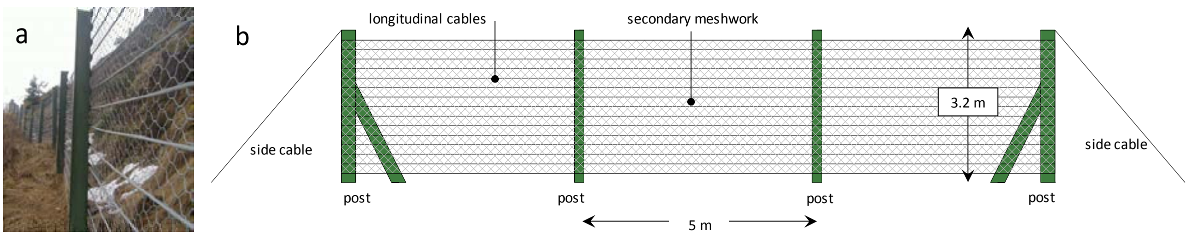

Fig. 1. The semi-rigid barrier considered in the study: (a) pictures and (b) view of the FE model.

2.1. Model details

The FE modeled barrier is 3.2 m in height and has 15 evenly spaced longitudinal cables of 12 mm diameter. Internal posts are IPE 200 while the external posts are IPE 300. Side cables were 18 mm. Three spans are considered, Post spacing is 5 m. The model is three-dimensional and made of one-dimensional elements, whose behaviour is implemented as three linear and elasto-plastic. Constitutive parameters were accurately calibrated based on the available experimental data, as follows: 12 mm cables E_0 = 105.5 GPa, E_1 = 36 GPa, ε_y = 1% ε_u = 2%, 18 mm cables

18 mm: E_0 = 133 GPa, E_1 = 50 GPa, ε_y = 1%, ε_u = 2%. In particular, the response of the hexagonal meshwork was modelled following comparison of numerical analyses with data of tests carried out on net portions [8]. The net may rupture, while the cables undergo indefinite deformation once the yielding threshold is reached. The posts have an elastic-perfectly plastic behavior according to the steel properties and with failure assigned at a strain threshold (IPE 300 and IPE 200: E_0 = 210 GPa ε_y = 0.11% ε_{ff} = 2%). The connection between structural elements have been modelled following the numerical strategy presented in [2].

2.2. Numerical analyses

The analyses were performed by impacting the model of the semi-rigid barrier with prismatic blocks of known mass and velocity, with the scope to identify the minimum value of kinetic energy at which the barrier fails. Failure condition are reached when the barrier is no longer able to arrest the impacting block, whose impact kinetic energy is, hereinafter, described as failure energy. In all the analyses, the barrier model stands in vertical position, according to its typical, on-site configuration and simulations include the application of the gravity force.

According to the notation introduced in Fig. 2, where schematic drawings of the explored impact conditions are shown, the analyses were run by varying, in a realistic interval, the following parameters: block external length (Fig. 2a), incidence angle (Fig. 2b) and location at impact (Fig. 2c). As for the block size, 8 different values of external lengths were taken into account (from 0.5 to 1 m). The inclination angle was varied between minus 60° to 60°, using 30° intervals. The impact location was varied within the central span, by moving the block upward and downward along the centerline, or horizontally as depicted in Fig. 2c. Explored positions were: 0.50 m upward, 0.5 m downward and 1 m left. Reference test condition is represented by a central impact of a 1 m block normal to the interception structure. Each parameter was varied while keeping the other unvaried.

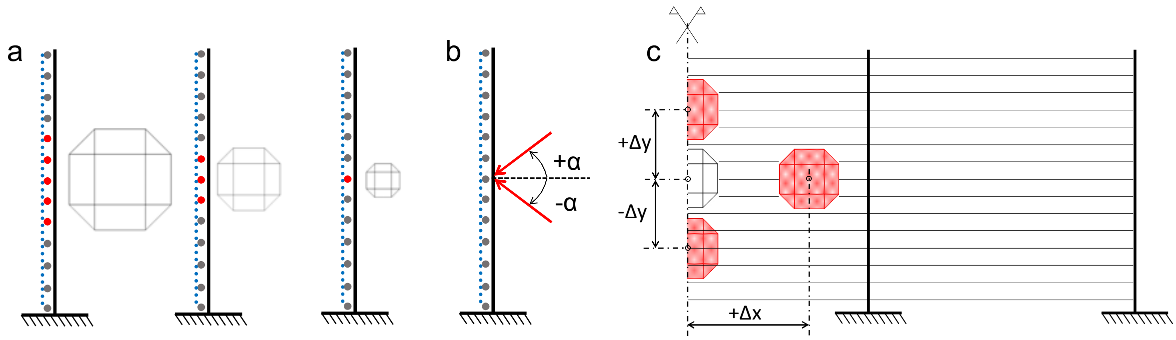

Fig. 2. Schematic drawing of the impact conditions explored in the analyses: (a) various block sizes; (b) various inclination of the block speed (c) various block positions.

2.3. Discussion of the FEM results

The analyses have shown that the numerical response of the considered semi-rigid barrier is significantly affected by the variation of the considered parameters. Observed values of failure energy varied between 80 kJ and 360 kJ. As for the block size, the maximum values of failure energy were associated to the largest blocks (from 0.8 m to 1 m of external length). Within this range, the impact energy remains approximately constant and equal to 250 kJ. A reduction in failure energy is observed as the block size is reduced. Medium size blocks (0.65 m to 0.75 m) produced failure with impact energy about 160 kJ. To bring the fence to failure, smaller blocks (from 0.5 m to 0.6 m) had to impact with failure energy equal to 80 kJ (Fig. 3a). The relation between block inclination of the trajectory and failure energy showed to be approximately linear, with the minimum value reached at an inclination of minus 60° (about 170 kJ) and a maximum value achieved at 60° (about 360 kJ) as depicted in Fig. 3b. Finally, the failure energy decreases to 220 kJ by moving the block impact location downward or upward along the centerline of 50cm (Fig. 3d), whereas a high energy (300kJ) resulted necessary to make the fence fail when moving the block 1 m left to the centreline (Fig. 3c).

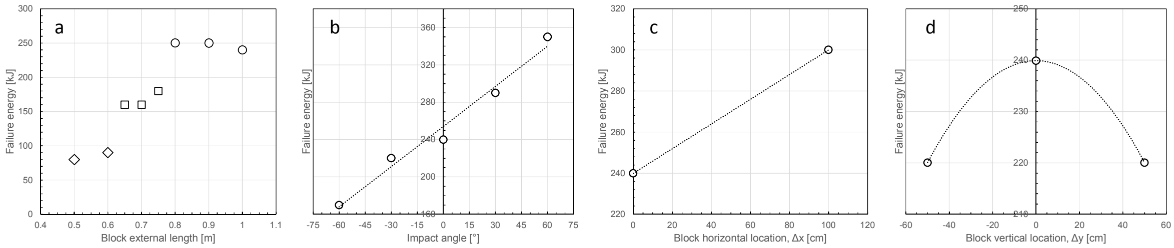

Fig. 3. Selection of FEM results: failure energy plotted as function of (a) external length of the impacting block (b) block velocity angle (c) horizontal position of the block with respect to the barrier centre and d) block vertical position along the centerline.

This trend can be explained with a different failure mode triggered by different impact conditions. As for the block size, the failure mode is related to the number of longitudinal cables involved by the impacting body during the simulation (Fig. 2a). The deformed shape of the barrier impacted by the 100 cm block and 50 cm block at failure are respectively depicted in Fig 4a and Fig. 4b. When the block velocity is inclined with respect to the horizontal, the failure mode is related to the angle sign. A downward movement of the block made the system fail by causing plastic hinges at the posts (Fig. 4d), while if the block is moving upward, it overcomes the net by rolling out from the top (Fig. 4c).

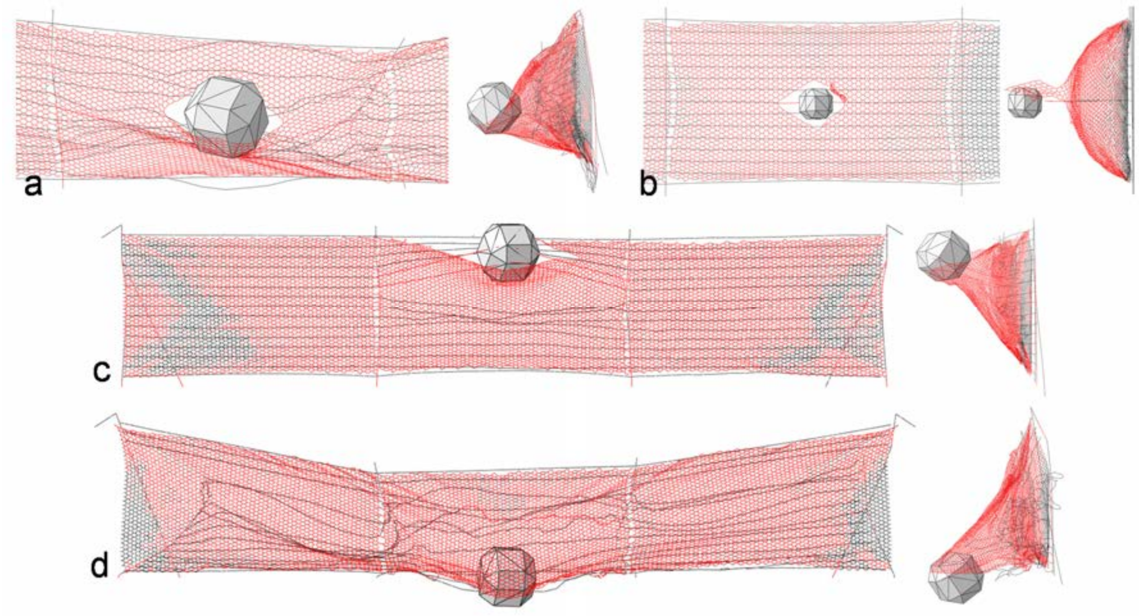

Fig. 4. Fence failure mode: block external length of a) 100 cm and b) 50 cm; block inclination of a) -30° and b) +30°, elements which has entered the plastic branch in red.

3. A probabilistic approach to describe the failure of a semi-rigid barriers

Preliminary results, presented in Section 2, have given an interesting insight on the numerical response of a semi-rigid barrier, characterized by a large dependence of the barrier response to the impact conditions. The block size, the inclination of the velocity and the block position induce different modes of failure of the barrier, which in turn result in different values of failure energy.

As a result, the barrier capacity cannot be established in a deterministic way. Aiming at describing more comprehensively the response of the semi-rigid barrier, a larger set of parameters and ranges was identified. Reliable impact conditions for rockfall protection barriers are those predicted by rockfall propagation models, according to which data were established, as described in Table 1, where 6 parameters and relative ranges are provided.

Table 1. Parameters and range for FE analyses.

parameters	range	unit
Volume	0.03 - 4	m^3
Velocity	5 – 40	m/s
Rotational velocity	0 - 35	rad/s
Vertical location	1 – 2.5	m
Horizontal location	0 – 7.5	m
Incidence angle	-1.05 – 1.05	rad

The lower threshold of the block volume is referred to an external length of 20 cm, a smaller block would easily pass through the longitudinal cables of the interception structure, while a block larger than 4 m^3 (mass of 10 ton) would rupture the interception structure in static conditions. The block centroid is then moved vertically from 1 m to the ground and then up to 2.5 m. The block is also moved horizontally along the central and side spans.

Any combination of the 6 parameters define a set of input data for a single simulation. On the total possible, a limited number of 300 FE simulations were selected, using a Latin Hypercube Sampling (LHS). This optimized technique, referred to as plan of experiment, allowed to sample in all parts of the range of each input parameter. It is a statistical method which enable to generate a sample of plausible collections of parameter values from a multidimensional distribution, typically used to appropriately plan a numerical campaign.

For each simulation the time history of block displacement, translational and rotational velocities were recorded. Based on these data, failure of the barrier model was associated with parameter

$$G = \frac{v_{final}}{v_{impact}} \tag{1}$$

where, output value v_{final} is the value of the horizontal component of the velocity at the end of the simulation and v_{impact} is the value of the horizontal component of the velocity at impact. The quantity was introduced and successfully used in [12]. Failure of the barrier model is associated to positive value of *G*, whereas, the barrier model has arrested the impacting block if *G* is negative.

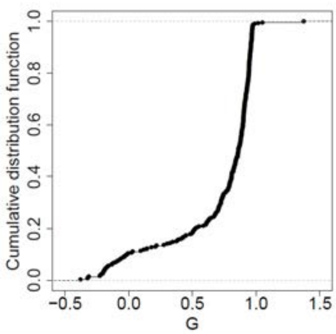

Fig. 5. Cumulative distribution of the G value for a semi-rigid barrier.

The preliminary study was intended as proof of concept, for the construction of a meta-model of the response of the semi-rigid barriers. To the scope the generalized polynomial chaos expansion (PCE) [13] was employed, by means of software Uqlab [14] and applied to the results of the analyses. From the meta-model, the performance of the semi-rigid barrier is described as a function of parameter *G*. With reference to the case study, early results are inserted in Fig. 5. As shown, the structure is efficient ($G < 0$) for a limited number of cases, considering the range of potential impact configurations. An interpretation as such is a convenient way to define the probability of failure of a semi-rigid barrier, which account not only for the block kinetic energy but for all the parameters which describe the block falling trajectories.

4. Concluding remarks

The paper has explored the response of a semi-rigid rockfall protection barrier by means of a numerical model. Preliminary analyses have been performed to investigate the influence of a few impact parameters on the barrier performance. In particular, the block size, the velocity direction and the block position produces different modes of failure, and thus different values of failure energy of the system. As a result, the barrier capacity cannot be established in a deterministic way as the nominal capacity of flexible rockfall barriers is generally identified. The effectiveness of these structures can be more successfully evaluated through a reliability probabilistic approach. Results can be used to create a meta-model of the barrier behaviour, which can be incorporated into rockfall simulation models. The meta-model aims at mimicking the response of the barrier accounting for the parameters related to the block trajectory. The procedure will improve the effectiveness of the calculation of the residual risks along roads while considering the barrier efficiency, thus providing a reliable tool to support a successful planning of rockfall mitigation interventions.

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